2007

# Using Organic Modeling Techniques to Create Scientific Models for Flow Analysis in Biomechanical Research: Exploring 3-D software typically used in creative media for model creation.

Jessica L. Weisman

ROCHESTER INSTITUTE OF TECHNOLOGY

Thesis Submitted to the Faculty of
The College of Imaging Arts and Sciences
In Candidacy for the Degree of
MASTER OF FINE ARTS

# Using Organic Modeling Techniques to Create Scientific Models for Flow Analysis in Biomechanical Research: Exploring 3-D software typically used in creative media for model creation.

By

Jessica L. Weisman

May 30, 2007

Chief Advisor: Glen Hintz

Glen Hintz

(Signature)

Date: ___________________

Associate Advisor: Jim Perkins

Jim Perkins

(Signature)

Date: ___________________

Associate Advisor: Risa Robinson

Risa Robinson

(Signature)

Date: ___________________

Department Chairperson: Don Arday

Don Arday

(Signature)

Date: ___________________

I understand that I must submit a print copy of my thesis or dissertation to the RIT Archives, per current RIT guidelines for the completion of my degree. I hereby grant to the Rochester Institute of Technology and its agents the non-exclusive license to archive and make accessible my thesis or dissertation in whole or in part in all forms of media in perpetuity. I retain all other ownership rights to the copyright of the thesis or dissertation. I also retain the right to use in future works (such as articles or books) all or part of this thesis or dissertation.

**Print Reproduction Permission Granted:**

I, Jessica Weisman, hereby **grant permission** to the Rochester Institute of Technology to reproduce my print thesis or dissertation in whole or in part. Any reproduction will not be for commercial use or profit.
Signature of Author: Jessica Weisman Date: ____________

***or***

**Print Reproduction Permission Denied:**

I, ______________________________, hereby **deny permission** to the RIT Library of the Rochester Institute of Technology to reproduce my print thesis or dissertation in whole or in part.
Signature of Author: ______________________________ Date: ____________

***optional addition***

**Inclusion in the RIT Digital Media Library Electronic Thesis & Dissertation (ETD) Archive:**
I, Jessica Weisman, additionally grant to the Rochester Institute of Technology Digital Media Library (RIT DML) the non-exclusive license to archive and provide electronic access to my thesis or dissertation in whole or in part in all forms of media in perpetuity. I understand that my work, in addition to its bibliographic record and abstract, will be available to the worldwide community of scholars and researchers through the RIT DML. I retain all other ownership rights to the copyright of the thesis or dissertation. I also retain the right to use in future works (such as articles or books) all or part of this thesis or dissertation. I am aware that the Rochester Institute of Technology does not require registration of copyright for ETDs.

I hereby certify that, if appropriate, I have obtained and attached written permission statements from the owners of each third party copyrighted matter to be included in my thesis or dissertation. I certify that the version I submitted is the same as that approved by my committee.
Signature of Author: Jessica Weisman Date: ____________

**Table of Contents**

## *I. Introduction*

Biomedical Engineering research utilizes digital three-dimensional models of human anatomical systems that are used as components in specific types of simulation. The data collected from the simulations provide quantifiable information that has a physical basis. The use of the digital models allow engineers the freedom of experimentation that may not be possible in the real world and allows them to quickly change the parameters. Although these models can provide reliable information, the models represent a mechanical ideal and therefore do not accurately represent organic matter. The consequence of using an ideal model to represent tissue may give flawed data, since the mechanical simulation does not identically represent living tissue. The purpose of this thesis was to develop the methodology and actual creation of a three-dimensional model that was a physically accurate representation of organic lung acinar tissue. The objective is to have the model input into analytical software that will calculate the flow dynamics of the organic tissue represented by the model.

Specifically, the model represents alveolar ducts in lung tissue. The model starts from the transitional bronchioles through the alveolar ducts and ends at the terminal alveolar sacs. Creating this model was challenging due to the microscopic size and inherent density of the tissue, making it difficult to determine structure.

Motivation:
Beyond the primary objective, this project gives new relevance and validity to the anatomical knowledge, research ability and artistic skill of the medical illustrator. The study not only brings in a medical illustrator to aid visually but; regards them as an important scientific contributor.
The medical illustrator working in three- dimensional modeling had to take on a new role, requiring both analytical and artistic skill. The subject matter was challenging and showed how visualization skills could be translated into something that can be used as a tool in research.

## *II. Methods*

Preliminary research:
The purpose of this research is to evaluate airflow, particle deposition and mixing in the acinar region of the respiratory tract. The ultimate goal of the research is to compare the effects of disease on respiratory mechanics specifically focused in the alveolar ducts and terminal alveoli. This research requires accurate morphometry of the airway walls.

Dr. Robinson's article; Experimental and Numerical Smoke Carcinogen Deposition in a Multi-Generational Human Replica Tracheobronchial Model; provided the basis that led to the hypothesis of this study. The article describes the use of a tracheobronchial model taken directly from a solid replica of excised human lung segments to create a digital and a physical hollow model. The models were used to investigate deposition of mainstream and sidestream cigarette smoke particles. The particulate sizes and content levels were measured and used to compare the simulation to the experimental data. Excellent agreement was found between the measured and predicted results. The results of this experiment led to the hypothesis that is the basis for this study. The organic representation of the upper airways proved to yield viable results, therefore a similar approach should be continued with the study of the acini. Due to the microscopic size of the acini, there are more challenges to their visualization. Size limitations of three-dimensional scanning technology and M.R.I. image stacks prevent direct replication of the casts like those done for the tracheobronchial study. The model must be built up from a variety of sources, including measurements documented in the Weibel[1] article, Morphometry of the Human Pulmonary Acinus and measurements in conjunction with visual information. This also includes personal observations and micrographs taken from actual cast samples magnified by a scanning electron micrograph.


*Example of micrograph showing structural complexity of alveoli*

The geometry used in dynamic air -flow simulation had previously been simplified to represent an idealized version of the acini model. The idealized version was based solely on averages taken from systematic sampling documented in the article. (Pg.299 Weibel[6])
This resulted in a model that was numerically accurate, but very mechanical in appearance. Comparing the idealized version of the model to micrographs of the actual tissue show almost two distinctly different structures. One might conclude by this visual comparison and the excellent results from the tracheobronchial experiments that unfavorable deviations in the results would occur.

*Note: Concurrent research is being conducting using an idealized model of the acini in both digital simulations and physical experiments. Results are pending at the time of this research.

The Weibel[1] article gives a written physical description of the structure of the acini and describes the attributes that define their function. The article documents the measurements that are based on averages of samples taken from various silicone casts made from human specimens. Definitive proof of the structure gave informative context to the actual samples used in this investigation. The casting process can be destructive and give anomalous information. An in-depth study of the article was necessary to be able to correctly identify the attributes that were expected and what may be divergent results.
Functionally, the acinar is defined as the largest airway unit in which all airways participate in gas exchange. Physically, Weibel defines the acini as originating at the "transitional bronchioles," which are identified as the transition from the conductive to the respiratory zone. (Pg. 402 Weibel[1]) There are three types of intraacinar airways: respiratory bronchioles, where only part of the surface is covered by alveoli; alveolar ducts; which are completely ensheathed by alveoli, and alveolar sacs, the blind-ending terminations of alveolar ducts. Various other studies showed some differences when reporting the locations of terminal sacs, but Weibel determines that these differences are not significant enough for further investigation and was probably due to incomplete filling of the casts. (Weibel[1], Pg 412) Weibel's descriptions were then compared against the human samples obtained by a research partner for this study. Certain important structural attributes were identified to gauge the parallels in comparison:

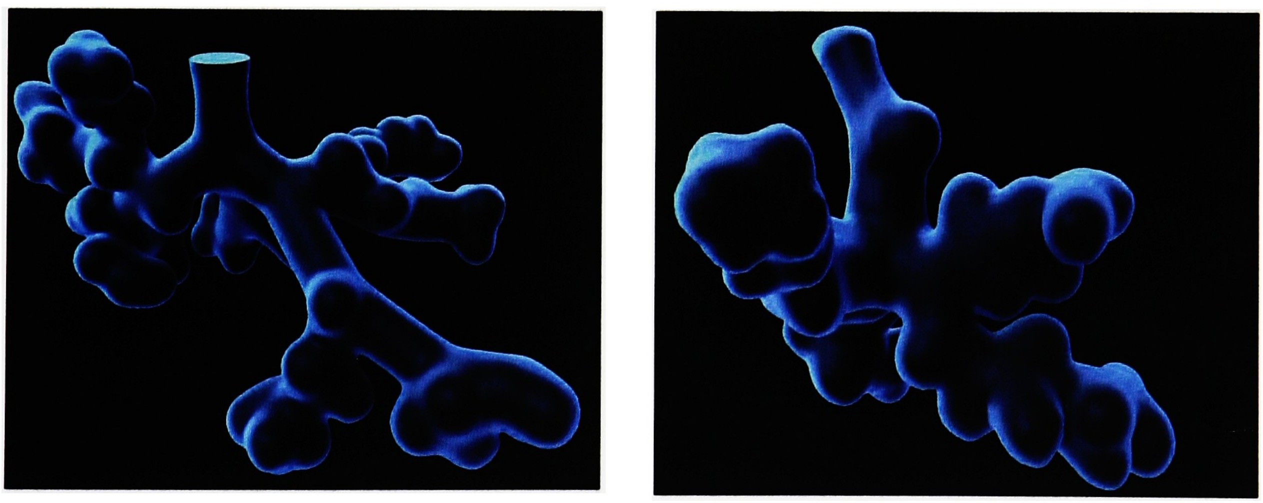
1. Size variability in both duct and sac length and diameter, found mainly in the first few generations.
2. Adjacent alveolar sacs share a membrane. Demarcation of a single alveoli is not always obvious.
3. Irregular dichotomous branching, with some trichotomous and polychotomous
4. Inter-digitation of the sacs and capillary networks cause shape distortion.

The observations made were in excellent agreement with what had been described.

Although Weibel provides a thorough description, further information was necessary to form a complete understanding. The true shape of the airspace of alveoli is difficult to determine because of their small size and ability to visualize them in a live being. The shape of inflated vs. deflated alveoli came into question. The importance of visually confirming shape changes at specific inflation levels was pivotal to creation of the structure.

Given the parameters established by Weibel, a replication of his process was used to verify data for this investigation. Varied results are sited in the article and recognize the potential for error. Also, visualization was difficult to decipher from the written description alone. The importance of visually confirming shape changes at specific inflation levels was pivotal to the creation of an accurate model. This lack of information led the next step in the research process to use rat lung casts to obtain real physical data

Casting Procedure:
The procedure was adapted from the article, “Casting the Lungs in-Situ.” ,Phalen[3] which describes the methods used to cast the lungs of a dog.
The process began with anaesthetizing the rat. The bodies must be freshly deceased for the tissue to respond as closely to living tissue as possible. (It is important to note here that fixed specimens were used in Weibels casts.) Rats were then pinned down in a supine position with all four legs splayed and pinned exposing the full area of the anterior surface. A sagittal cut was then made from beneath the jaw down to just below the diaphragm, about 1mm below the palpable termination of the ribs . The fur and skin was then carefully peeled away exposing the most superficial of the musculature. A transverse cut was made along the neck carefully detaching the muscle attachments. The trachea was then exposed and slit halfway through leaving the posterior wall intact. A small tube was inserted into the trachea and secured with a piece of thread. The silicon mixture was prepared and a 5ml syringe filled in measured amounts. The procedure was done four times at four different levels of inflation with corresponding amounts of silicone. The plastic, flexible tubing inserted into the rat was then attached to end of the syringe. First, $CO_2$ is pumped throughout the respiratory system to get rid of any remaining oxygen. Next, saline solution is put in at the predetermined amount based on levels on chosen inflation. The inflations were 25%, 50%, 75%, and 100% of the rat’s lung capacity. The levels were chosen to be able to easily compare shape change and dimensions to Weibel[1]. The silicone displaces the saline, saline diffuses through the tissue and silicone takes its place, which fixes the lung inflation level. The silicone cures overnight and is subsequently dissolved in an alkaline and then acid solution to eat away remaining tissue.
Initial observations of the casts are made using a stereoscope. The process of sketching is begun at this stage in order to document anything that can be learned from the differences in the casts.



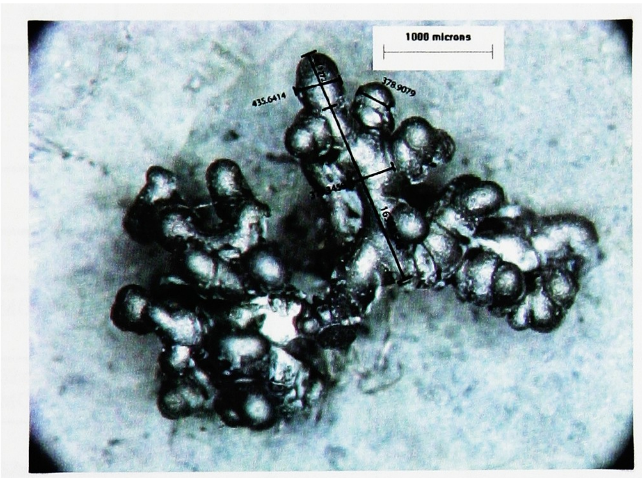
*Preliminary model based on hand drawn sketches*

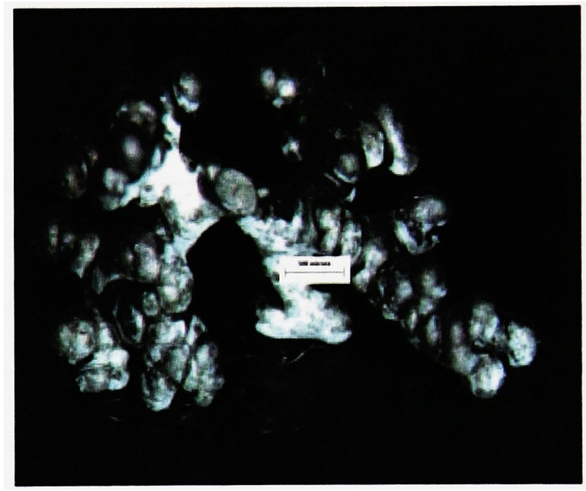
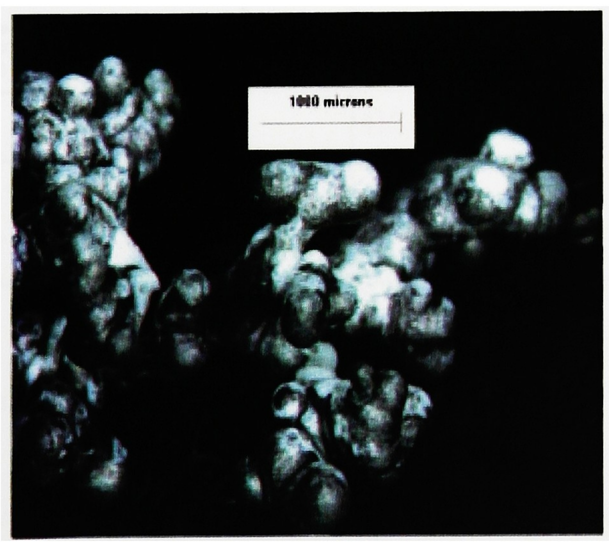
Conclusion:
The samples showed a significant difference in how filled the alveoli became due to set inflation levels and therefore effected shape change. The levels chosen proximately reflected tidal volume, vital capacity, forced tidal capacity and total lung capacity. It was observed that the less volume injected into the lung, the less round the alveoli became. It was also determined that the silicon did not reach every part of the lung evenly. (It should be noted that Weibel states that the fluid- filled lung expansion levels are a small percentage smaller then air-filled.) This could conclude that tidal volume during normal breathing was not reflected the cast shape described in the article and was closer to a total lung capacity shape. The information this provided will determine certain pressure parameters set up for the experimental stage performed by the engineering team members.

Human Samples:
Although rat lung alveoli were studied to gain insight into the shape change to inflation ratios, human samples were used to create the structural foundation for the final model. The samples were obtained from Michael Oldham at the University of California at Irvine, Dept. of Community and Environmental Medicine. The Human lung casts were taken from a fresh cadaver at an estimated 90% inflation level.

The inflation levels were determined based on what had already been determined. Four Samples were chosen to investigate further and viewed in the scanning electron microscope. Due to the complexity and density of the samples, it was decided that the sample that clearly displayed the key attributes would be used.
The sample clearly showed transitional bronchioles, alveolar ducts and sacs (individual and clustered). Most samples of this tissue are very difficult to discern through observation due to density and indeterminate borders.

The chosen sample, *MO-1* was imaged under both the SEM and stereoscope at various angles to get a clear three-dimensional understanding of the structure.
Measurement software that was built into the digital stereoscope was used to take approximate measurements. Measurements were compared to Weibel's data and it was concluded that his inflation level was at approximately 75%.



*Various stereoscope images of MO-1 showing measurements*

In comparison the sample, *MO-1* measured at about 15% larger than the average given by Wiebel, or 90% inflation. This corresponded with the information that was provided by the source of the sample.
These adjustments were taken into consideration to compensate for the 15% discrepancy when creating the final model structure.

| | Weibel et al 1988, Table 3, p.408 75% inflation | | 90% inflation, Weibel | | Radii | | Radii, cm | | size reference | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | duct | sac | duct | sac | duct | sac | duct | sac | duct | sac | |
| 1. | 292 | 224 | 336 | 336 | 167.9 | 128.8 | .016 | .012 | | | |
| 2. | 325 | 260 | 374 | 374 | 186.87 | 149.5 | .018 | .014 | | | |
| 3. | 323 | 255 | 371 | 293 | 185.72 | 255.07 | .018 | .025 | | | |
| 4. | 313 | 262 | 360 | 301 | 179.97 | 150.65 | .017 | .015 | | | |
| 5. | 310 | 229 | 357 | 263 | 178.25 | 131.67 | .017 | .013 | | | |
| 6. | 336 | 255 | 386 | 293 | 193.2 | 146.62 | .019 | .014 | | | |
| | | | 90% inflation, *sample MO_1 | | | | | | | | |
| | | | | | | | | | | | |
| | 32xcoated alveoli MO_01.jpg | d1= | 308.42 | | 154.21 | | .015 | | | | |
| | | d2= | 402.34 | | 201.17 | | .020 | | | | |
| | 32xcoated alveoli MO_01_05.jpg | | 379.34 | | 189.67 | | .018 | | | | |
| | 32xcoated alveoli MO_01_06.jpg | | | 435.64 | | 217.82 | | .021 | | | |
| | | | | 305.72 | | 152.86 | | .015 | | | |
| | 32xcoated alveoli MO_01_03.jpg | | | 371.95 | | 185.97 | | .018 | | | |
| | | | | 413.34 | | 206.67 | | .020 | | | |
| | | | | | | | | | | | |

*Chart shows compared dimesions to Weibel*[1]

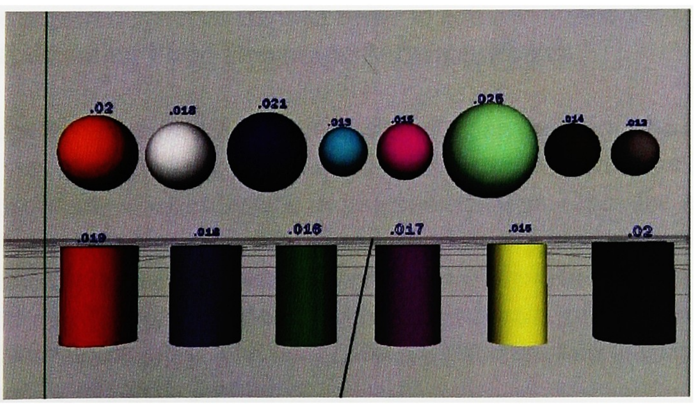
## III. *Technical*

Modeling process:
The model created for this study originates at the point of the transitional bronchioles and ends at the terminal alveolar sacs. The tissue is extremely dense and it is difficult to identify important structural attributes, therefore it was decided that the model would follow one generational pathway to its terminal end. This simplification clarifies the structure, improves accessibility to take more accurate measurements and allows the model to be viable when used in the flow dynamics simulations.

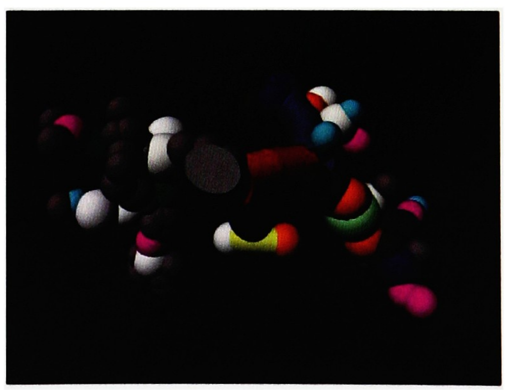
The model is to be translated into a volume mesh and decomposed for use in a fluid dynamics analysis program. The commercial software package, Autodesk Maya was used as the primary modeling program. Typically, commercial three-dimensional modeling software, such as Maya, is aimed at creative industries. The software uses interactive interface approach to building a model, which is markedly different from creation using engineering software. Creation requires an artists' understanding of spatial relationships and form. The freedom to interactively manipulate individual points, faces and edges allows the creation of an organic body.
Conversely, typical engineering visualization software only allows rigidly placed coordinate points that must be numerically input in order to create a working volume. This results in a model that is accurate numerically, but visually mechanical. Using Maya provides a unique solution to this problem. It has tools that satisfy both the need to be numerically accurate while providing the freedom to create a model with an organic shape. The freedom to interactively manipulate individual points provides the control that is necessary for the desired result. Similar to the tools in the engineering software, Maya also has the ability to input and take measurements to control accuracy. Additionally, the wide variety of export file options available (Ex. .obj, .stl, .vrml, .dxf, iges) in Maya makes it possible to transfer files between software packages.

Although, Maya does enable a high degree of complexity for the model, it does cause some difficulty in the workflow process. The process of visualization began by simply sketching the sample at different angles to get a basic understanding of the structure. A rough model was then built solely based on the sketches. This gave a basic understanding of what shape and size the final structure would result.
Next, a way that quantified and supported the dimensions of the model needed to be created in order to give validity to the potential results of the simulation experiments.
Through a combination of self- made measurements using the software in the digital stereoscope, scale references embedded into the SEM images and averages in Weibel, a valid model could be produced. (Any unknown measurements due to limitations of the measurement software were filled in using template based on averages in Weibel[1]. This ensures that all measurements had been confirmed.)

*A.*



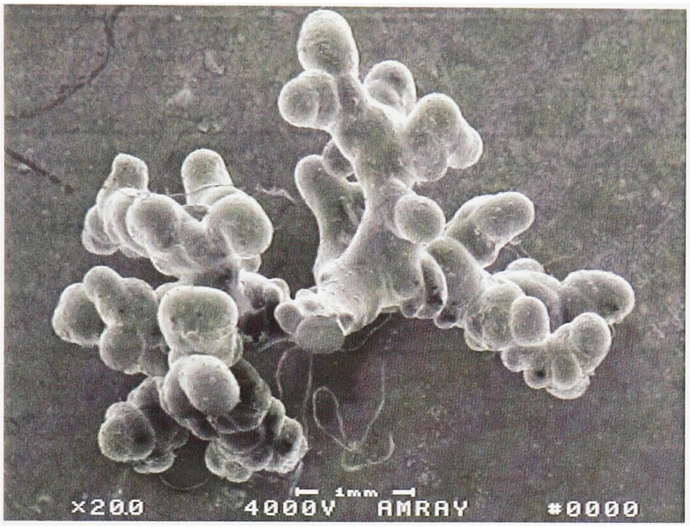

*B.*



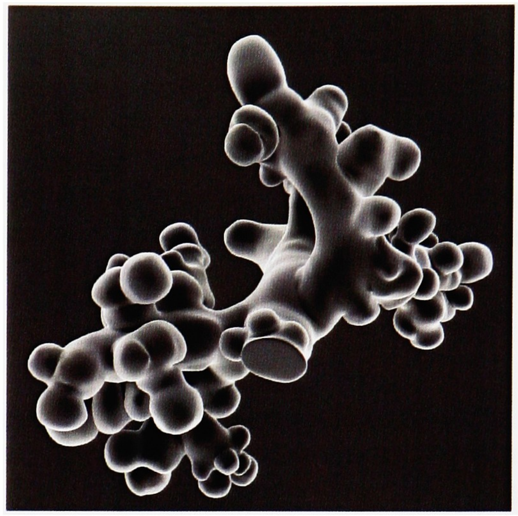
*A. Three-dimensional template components*
*B. Color coded template model provides quantifiable data at specific points in the model*

The decision was then made to use the SEM photos of MO-1 as a visual reference for the creation of the final model. Visual comparisons to the SEM images were confirmed by using similar camera angles manipulated in Maya's three –dimensional environment. This allows for complete views the model's angles and size relationships.

*A.*




*B.*



*A. Micrograph of sample MO-1*
*B. Rendered image of model*

File Testing/ Processing Techniques/ Technical Issues:
The process that creates a working model is a complex series of steps that must be translated through several software programs. The process followed in this study that successfully translated the files is as follows: Maya - Vp Sculpt – Harpoon –Fluent. The other process that is yet to successfully translate the files: Maya – Vp Sculpt – Solidworks – Gambit – Fluent.
Both processes have problems that have not yet yielded the results this study was expecting.

Maya is a surface modeling program that uses vertices, faces and edges to create the shape. The conversion to a volume required specific steps in order to achieve a model whose physical properties could be recognized by the CFD (Calculating Fluid Dynamics) software, Fluent.

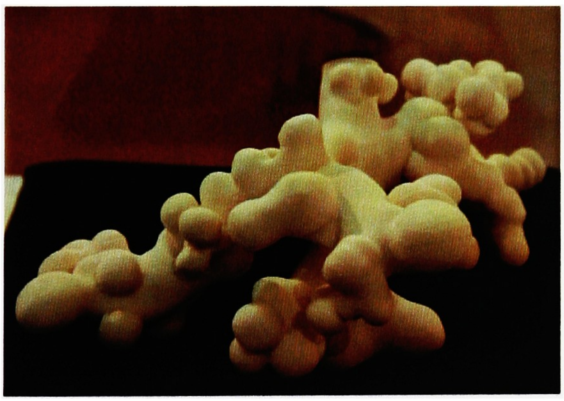
The steps began with Maya for the modeling stage. Next, the model was brought into Vp Sculpt as an .obj file, which was used to clean up the model. This step is used to fix holes and remove non-planar surfaces, which can cause problems in calculations in proceeding steps. Once the model is cleaned up it is then exported as a .stl file and brought into Harpoon. Harpoon is a relatively new software package that is used to both create a volume and mesh for the model. The meshed volume provides the boundary information that allows Fluent to make its calculations. Because Harpoon is a newer software package, its meshing properties and reliability have not yet been tested thoroughly. The data gathered from the simulations based on Harpoon's meshing are not yet reliable and must be explored further.

Harpoon's website describes its application for the type of technical issues confronted in this study. Harpoon's website addresses the issue of meshing complex geometry.

> *Biological systems are often defined by complex 3D geometry. In many cases, geometry motion is involved. The source of geometry may be from CAD systems, but it may also be from medical imaging, converted to point clouds or triangulated surfaces. All such cases require a mesh generator that deals well with complex geometry. CEI's extreme mesher, Harpoon, is increasingly proving itself to be well adapted to such problems.*

An alternative process was also followed using tested methods, but due to memory restraints related to the density of the model, it has not yet been successfully executed. The model once exported from Vp Sculpt is then brought into Solidworks as a .stl in order to create a volume model. This step is where the issue of lack of memory and density of the model did not allow Solidworks to create the file necessary to continue with this method of file conversion. Theoretically, the file would then be exported as an .iges file and imported into Gambit. Gambit is a well-tested meshing program that works in conjunction with Fluent to get the best conditions possible for calculating the fluid dynamics in a volume.

Additional testing:
The digital simulation is just one method of testing the model for accuracy. Physical experiments are also part of the process and achieved by creating a rapid prototype from the computer-generated model. The rapid prototype can then used as a mold to create flexible model from silicone that will emulate the process being investigated for this study. Also, the prototype can be used to confirm measurements that can be easily made at the larger scale for comparison to the data.



*Photos showing rapid prototype*

## *IV. Conclusions/ Future*

Due to the ongoing nature of this project, there will be a continuation of the study to streamline the process and refine the model. Various meshing techniques are yet to be explored. New meshing software, such as Harpoon has not been effectively tested against more established programs and so cannot be verified as a viable tool. Therefore, verification of the digital simulation and the physical experiment has not yet been documented. Additionally, several modeling software packages are also under investigation in order to further streamline the workflow. Potentially, using a program that can handle both surface modeling and volumes would be an ideal solution, instead of having to use multiple programs.

## i. Bibliography

[1] Haefeli-Bleuer, B, and E R. Weibel. "Morphometry of the Human Pulmonary Acinus." Anatomical Record 220.4 (1988): 401-414.

[2] "Harpoon - Automatic Extreme Mesher, Simplifies, Speeds Grid Generation for FEA and CFD." CEI - Global Scientific Visualization Leader. May 2007 <http://www.ensight.com/harpoon.html>.

[3] Phalen, Robert F., Hsu-Chi Yeh, Otto G. Raabe, and David J. Valasquez. "Casting the Lungs in-Situ." Anatomical Record 177 (1973): 255-264.

[4] Robinson, Risa J., Michael Oldham, Rodney Clinkenbeard, and Pravir Rai. "Experimental and Numerical Smoke Carcinogen Deposition in a Multi- Generational Human Replica Tracheobronchial Mode." Annals of Biomedical Engineering 34.3 (2006): 373-383.

[5] Sapoval, Bernard, M Filoche, and E R. Weibel. "Smaller is Better - But Not Too Small: a Physical Scale for the Design of the Mammalian Pulmonary Acinus." PNAS 99 (2002): 10411-10416.

[6] Weibel, Ewald R. "Morphometrics of the Lung." Handbook of Physiology. 1964. 285-307.

## ii. Acknowledgements

Michael Oldham, University of California at Irvine, Dept. of Community and Environmental Medicine,
Richard Doolittle, Rochester Institute of Technology, Dept. of Health Sciences
Dave Fisker and Michael Haselkorn, Rochester Institute of Technology, CIMS
This work was sponsored in part by a grant from the Phillip Morris External Research Foundation, International (Principal Investigator: Risa J. Robinson, Ph.D., Dept. of Mechanical Engineering, Rochester Institute of Technology) and by the Vesalius Trust